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AURORA FLASH X-RAY FACILITY AS A SOURCE-REGION EMP SIMULATOR

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The study of source-region electromagnetic pulse phenomenology and coupling[1-4] is distinguished from more conventional electromagnetic research by the presence of time-varying air conductivity. The relevant Maxwell equations are:

$$\varepsilon\nabla\cdot E=\rho,$$
$$\mu\nabla\cdot H=0,$$
$$\nabla\times E=-\mu\dot{H},$$
$$\nabla\times H=J+\sigma E+\varepsilon\dot{E}.$$

These can be combined into a wave equation for the electric field:

$$\nabla^2 E-\mu(\varepsilon\ddot{E}+\sigma\dot{E}+\dot{\sigma}E)=\mu\dot{J}+\nabla(\rho/\varepsilon).$$

(The magnetic field can be found by time-integrating $\nabla\times E$.) The first two terms appear in the well-known homogeneous wave equation:

$$\nabla^2 E-\frac{1}{c^2}\frac{\partial^2 E}{\partial t^2}=0,$$

where $c^2=\frac{1}{\mu\varepsilon}$.

The third term represents the dissipation of energy resulting from air conductivity -- ie; the collision of charged free carriers (electrons and heavy ions) with neutral molecules. When this term dominates the second, the system becomes overdamped and is described by the diffusion equation:

$$\nabla^2 E-\mu\sigma\frac{\partial E}{\partial t}=0.$$

The fourth term contributes only when σ is time-varying,

and even then is significant only when the time-variation is as fast or nearly as fast as that of E(t). (Note that the third and fourth terms together represent $\frac{\partial}{\partial t}(\sigma E)$ -- the time-derivative of conduction current density.)

The right-hand-side terms represent the electromagnetic sources. In the case of nuclear EMP, these sources are provided by high-energy radiation from a nuclear device -- through the mechanism of the Compton effect (which leads to space current and charge separation) -- and by current and charge density induced in local or distant objects (including the ground). The region in which $\vec{J}(\vec{x},t)$ and $\rho(\vec{x},t)$ are non-zero is called the source-region, and the term "source-region EMP" is used whenever these local drivers are significant. In a typical burst, the source-region may be several miles in linear extent, and sources throughout the region contribute, through the well-known mechanisms of electromagnetic radiation and diffusion, to the fields at any given point.

This last observation lies at the heart of the greatest challenge to successful SREMP simulation. Powerful sources of [illegible]-energy puls[illegible] [illegible]ation (eg; A[illegible], and Herme[illegible]) are available, an[illegible] naturally pr[illegible] Compton current [illegible] charge separation [illegible] air (or ot[illegible]) into which the radiation is released. There is a temptation to assume that if these local sources are reasonably well reproduced, the full electromagnetic environment will be also. This naive assumption neglects the contribution of "distant" sources that cannot be reproduced, since existing pulsed-radiation technology is capable of irradiating a volume whose linear dimensions are expressed in tens of meters at most. (The AURORA test cell measures 20m×12m×5m.)

Of course, due to the finite velocity of light, the "prompt" environment <u>can</u> be reliably reproduced. However, after 10 nanoseconds or so, the absence of sources at a distance of more than 10 feet from the field point becomes noticeable. In addition, if the simulation testing is performed in a volume enclosed by metal walls (as in AURORA), this effect is aggravated by the electromagnetic boundary conditions imposed by these walls. They short out the electric field. Figure 1 compares (not to scale, but schematically) the AURORA test cell volume to the vast distribution of Compton electron source currents in an actual SREMP. Figure 2 is a schematic view of the inside of the AURORA test cell during a shot.

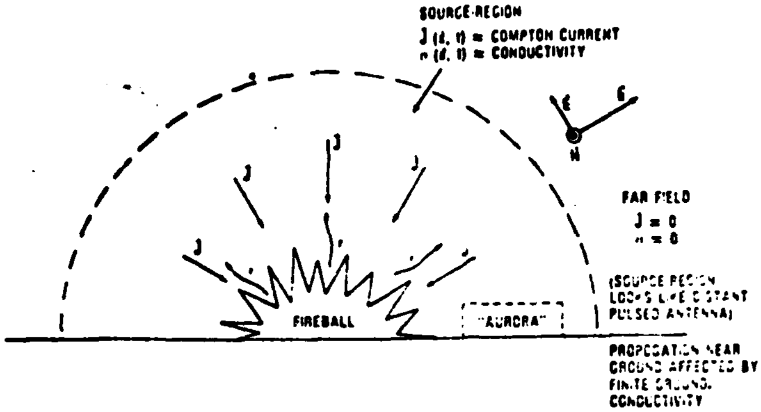

Figure 1. Comparison of small volume of the AURORA test cell with the vast distribution (several miles diameter) of Compton current drivers in an actual SREMP. Actually, the relative size of the test cell is much smaller than shown in the figure.

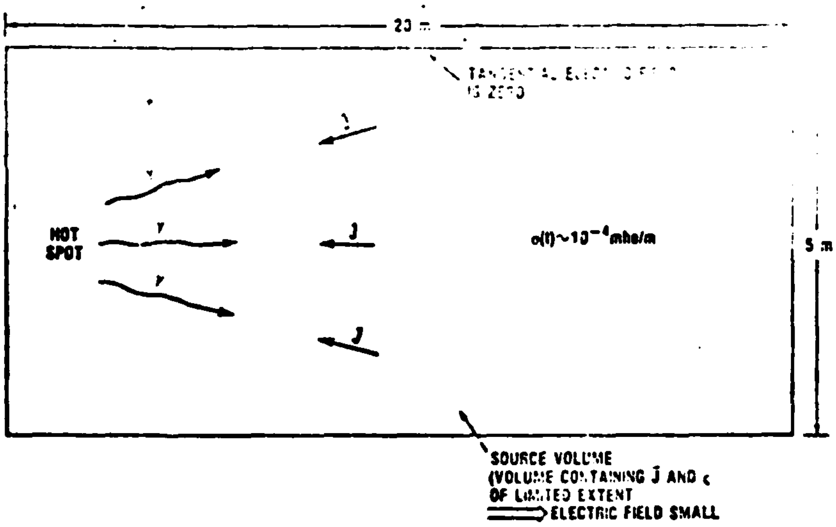

Figure 2. Schematic view of the AURORA test cell during an AURORA shot. The metallic test cell walls can short out the electric field generated by the Compton electrons.

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A less subtle limitation of facilities like AURORA is that the radiation pulse itself does not faithfully reproduce the pulse produced by a nuclear weapon. It rises more slowly and decays more quickly. The gamma spectrum is not quite right. The late-time drivers are very different, largely due to the lack of neutrons.

In spite of these limitations the authors, who have for several years been conducting an experimental program at AURORA,[9-27] have found that useful and relevant work can be done there. AURORA is a fine source of "basic physics" data on SREMP environments and coupling. Further, we believe that testing of the nature described here should be incorporated in any plan for SREMP vulnerability assessment and hardness validation of military and civilian electrical and electronic equipment. While ultimate determination of vulnerability and hardness will rely also on computer calculations, we feel that AURORA testing plays an essential role, both in validating the codes, and in exposing unexpected vulnerabilities.

SREMP environments can, in a rough way, be described as belonging to one of two categories -- tactical or strategic. These two types of environment, and several approaches to their simulation, will be discussed in turn.

The Tactical Case

Tactical source-region EMP is the electromagnetic component of a nuclear environment in which a soldier can reasonably be expected to remain alive and functioning for a useful time. Thus, tactical equipment, for use in a battlefield, is typically hardened only to a level consistent with a "man-survivability criterion." In practice, this normally means that peak conductivity levels of more than 10^{-3} mho/m are of no interest. (Long cables, which may channel energy from the "deep source region" out to a less highly dosed area, is an exception to this general rule.)

Some rough indication of the time-evolution and magnitudes of relevant parameters in the tactical case is given by the graphs of figure 3. These are taken from calculations made using LEMP[28] (a highly respected environment code in general use by the EMP community) and assuming a set of device characteristics[29] which describe no existing weapon, but can be taken as typical.

The primary driver is of course the dose-rate, $\dot{\gamma}$, expressed in units of rads/s. Thus, the $\dot{\gamma}$ pulse shape determines the shapes of all relevant time-histories -- i. e., $\vec{J}(\vec{x},t)$, $\sigma(\vec{x},t)$, $\vec{E}(\vec{x},t)$, and $\vec{H}(\vec{x},t)$.

In early time, the most significant descriptive parameter is the 10%-90% rise-time. This rise-time, typically on the order of 10 nanoseconds, is critical to the efficiency of resonant coupling to relatively small objects, with linear dimensions of ten feet or so. Most Army equipment (such as radios, vehicles, shelter-resident fire control systems, etc.) falls into this category.

In late time, the pulse can be described by one or more exponential decay constants. These decay times are much longer than the rise-time. At late time, the resonant behavior of "small" objects is not relevant, and such objects can be regarded with considerable accuracy as simple current collectors -- driven directly by a combination of Compton and conduction current. (Displacement current, important at early time, is of practically no significance at late time.)

Such "small" objects are ideally suited for testing in a facility such as AURORA. They can easily be transported to, and mounted in, the test cell. However, the limitations discussed earlier -- the slow pulse rise and the fast pulse decay -- make certain coupling behavior impossible to observe using AURORA in its conventional, unmodified state. The authors have, however, greatly enhanced the usefulness of AURORA for such small-object testing by introducing into the test cell auxiliary sources of electromagnetic excitation.[18] For very small objects, this may simply take the form of a pair of thin aluminum plates to which a high-voltage pulse is applied (figure 4). In this way, the proper electric field is reproduced in the enclosed volume, and the AURORA pulse serves the function of producing the radiation-induced conductivity and Compton current. The plates are made of aluminum foil in order to minimize shielding, space-charge effects, and other evidences of interaction between the radiation pulse and the auxiliary simulator. If the proper electric field is reproduced in this way, useful coupling measurements can be made on small systems -- measurements which include the effects of time-varying air conductivity. (The conductivity pulse, though it cannot precisely reproduce the threat conductivity pulse, does (1) permit the experimenter to learn more about the "basic physics" of such interactions, and (2) provide a test-bed for validation of theoretical techniques -- both analytical and numerical -- for predicting SREMP responses of simple geometric forms, and, most importantly, of systems.)

In undertaking a simulation such as the one described above, one must take care to maintain control over the environment by minimizing any interaction between the conductivity pulse and the auxiliary simulator. In the parallel-plate structure described above, the interaction mechanism is simply that the radiation produces a conductive path across the plates -- ie; a time-varying conductance appears in parallel with the capacitance characterizing the simulator structure. This time-varying conductance has the value:

$$G(t)=\frac{C}{\varepsilon}\sigma(t),$$

where C is the plate capacitance. One can ensure that the appearance of this shunting conductive path produces only minimal distortion of the driving electric field seen between the plates, by incorporating into the structure a low-value resistor, R, such that:

$$R<\frac{\varepsilon}{C\sigma_{max}}.$$

(See figure 4, where the 10-[illegible] purpose.)

The authors have used the approach described above, using two 8ft×4ft aluminum foil plates separated by [illegible] to excite a helical slow-wave structure intended to model a long cable or wire over ground. A 100-kV, 20-ns rise-time, 2-μs fall-time pulser (built by Pulsar) was used to drive the system. The behavior of the simulator was monitored by a number of current sensors, by two single-ended E-field sensors mounted on the grounded plate, and by a balanced sensor suspended between the two plates.

Of course the parallel-plate structure is in fact not a capacitor, but has some transmission-line characteristics. For the small simulator described above, these can reasonably be neglected, but for the testing of larger objects a larger structure is required. Work has been done in AURORA using a 10-m-long (3-m plate separation) structure,[17,18] whose inductive behavior cannot safely be ignored (figure 5). The circuit of figure 6 is a more appropriate approximation for this case. An example of the radiation-induced distortion seen in such a structure is shown in figure 7.[17,18] The inductance present in the system, in attempting to maintain current at a constant level, causes a voltage overshoot when

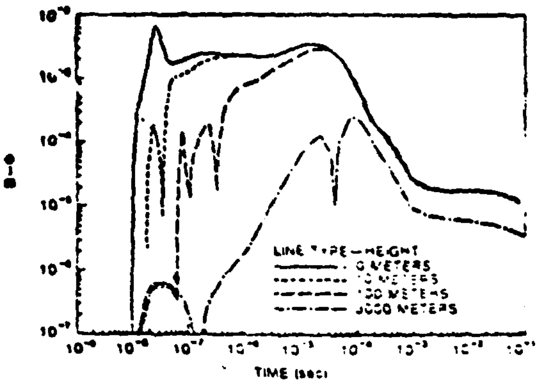

Figure 3. Typical time evolution of the magnetic field at various altitudes in the source region.

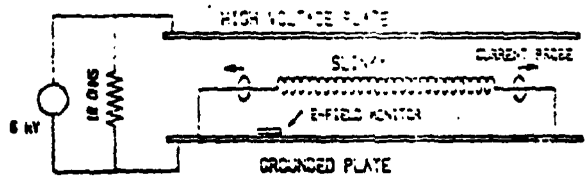

Figure 4. Simple parallel plate capacitor auxiliary field producer. The auxiliary field producer compensates for the tendency of the test cell walls to short out the electric fields. The "slinky" is, in this case, the test object.

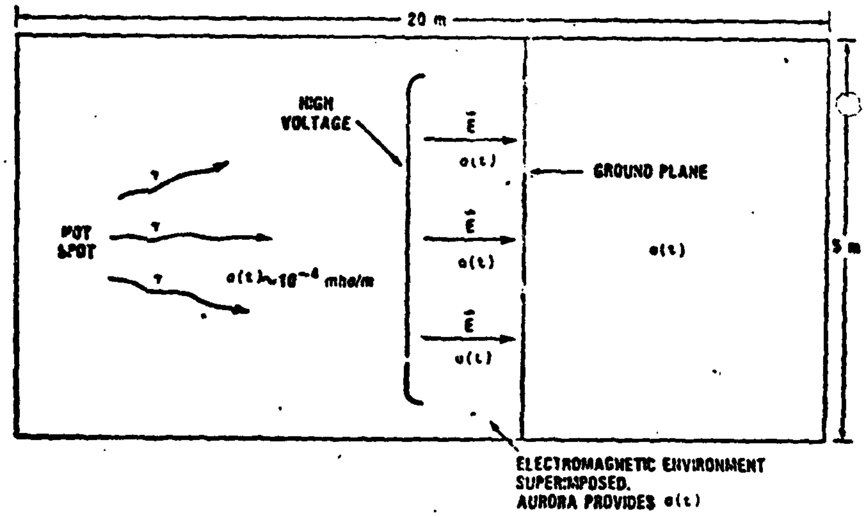

Figure 5. Schematic view of a transmission line designed to produce an auxiliary threat-relatable field in the AURORA test cell.

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the air conductivity drops abruptly. The authors have proposed, but not fully tested, a scheme for dealing with this more difficult problem. The low-impedance shunt must now be distributed rather than lumped, and of course it must also be insensitive to radiation. This is achieved by introducing a low-impedance non-ionizing "slave" transmission line (patent pending[28]) in parallel with the "master" working line. This technique is described in greater detail elsewhere.[17,18,28]

Examples of simple coupling measurements showing short-antenna response in the [illegible]-meter parallel-plate line, with and without radiation-induced time-varying air conductivity, are shown in figure 8.[17,22] The effect of conductivity is clearly seen here. It damps out the resonant displacement-current-driven response, and at the same time superimposes a conduction-current-driven response. The authors have devised and experimentally verified an equivalent circuit technique which can be used to describe the interaction of antenna structures to an electromagnetic pulse in a medium with time-varying conductivity.[16,17,19,20,23,24,27]

The Strategic Case

The above approaches using auxiliary EMP sources are useful ways of creating the desired electromagnetic environment while simultaneously superimposing a time-varying conductivity. (It should be noted that this isolation comes at a price -- the "wastage" of a considerable fraction of pulser energy.) However, if the conductivity level gets too high (such as might be required for a deep-source-region or strategic simulation), the conductive air will begin to shield the plates from one another. The relaxation time, ϵ/σ , must be kept relatively long (greater than, say, 10 nanoseconds) for the duration of the AURORA pulse. But, for a "strategic" level of 0.1 mho/m at peak, the relaxation time can drop as low as 0.1 ns. Under such conditions, it is said that "local effects dominate" (figure 9), and even if one can maintain the proper voltage separation across the plates, the intervening medium will short it out.

It is useful to note that the condition that "local effects dominate" is equivalent to the condition that Maxwell's wave equation degenerates into the diffusion equation, through the operator substitution:

$$\epsilon\frac{\partial}{\partial t}+\sigma \to \sigma .$$

Then $$\nabla^2 E=\mu\sigma\dot{E}.$$

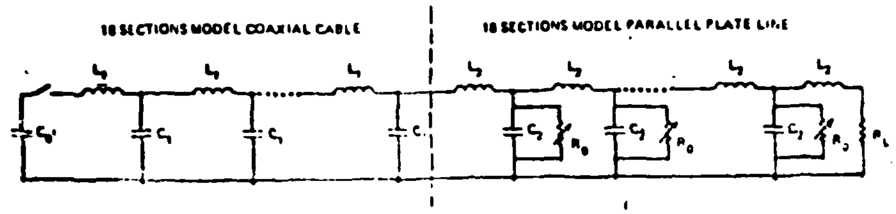

Figure 6. Schematic of transmission-line lumped parameter network model. The variable resistors represent the presence of air conductivity.

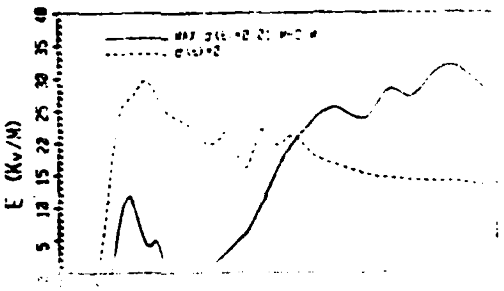

Figure 7. Extreme example [illegible] the effect of conductivity on the electric field in the Mark I S[illegible] simulator. First the air conductivity produces an undershoot in the line's electric field by shorting the transmission line: then the inductance of the line produces an electric field overshoot (inductive kick). The "slave line" of the proposed Mark II simulator is designed to reduce the undershoot and inductive kick.

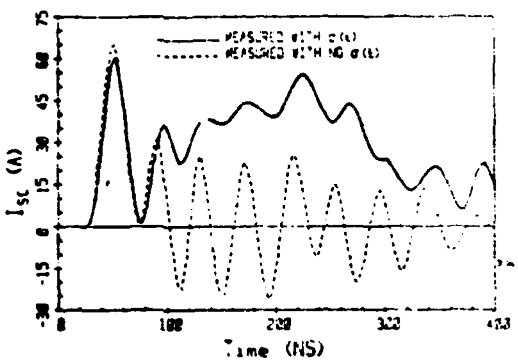

Figure 8a. Comparison of measured short-circuit monopole antenna response (2.42m) with and without time-varying air conductivity.

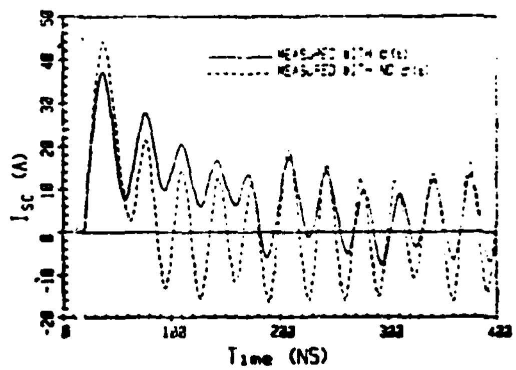

Figure 8b. Comparison of measured short-circuit monopole antenna response (2.21m) with and without time-varying air conductivity.

This applies when:

$$\sigma > \varepsilon \frac{\partial}{\partial t};$$

ie; when:

$$\frac{\varepsilon}{\sigma} < T,$$

where T is the shortest rise or fall time to be found in the driving signal. (Naturally, there is an intermediate case in which neither conductive nor displacement current can be neglected, but consideration of the two extremes is useful for a qualitative understanding.)

When "local effects dominate," truly local drivers are needed to maintain a field. In the case of nuclear EMP, sustained Compton current performs this function. In the AURORA, the authors, in collaboration with S. Graybill, K. Kerris, D. Whittaker and other Aurora staff members, have achieved this effect by using direct electron injection.

AURORA's five megajoules of stored energy appear at the vacuum diode as a pulse of electron current. Ordinarily, a high-Z (usually tantalum) target is used to convert to X-ray energy. This is an *inefficient process* (assuming one's goal is to irradiate the test cell as heavily as possible) because:

(1) bremsstrahlung conversion efficiency at machine voltage is only about 6%, the remaining energy being lost as heat in the target, and

(2) the X-ray range is on the order of hundreds of meters, so that further energy is lost heating up the back wall.

If the target is removed, and replaced with a 1/16th-inch steel vacuum-to-air interface, the electrons are released directly into the test cell, and these inefficiencies are avoided. There is no conversion loss, and the electron ranges are of the order of the test cell length. Problems of self-consistent beam propagation (eg, pinching and hosing) do not pose a threat, as has been determined in a series of AURORA experiments.[22]

In addition to thorough mapping of the electron irradiation of the test cell in a number of diode configurations and combinations,[22] coupling measurements have been made (by the authors) on aluminum cylinders, both vertical and horizontal.[23] Examples of these measurements are shown in figure 10. Interpretation of the results is far from straightforward, since a number of drive mechanisms contribute. The most important of these are:

(1) displacement current (early time),

(2) conduction current,

(3) Compton current, and

(4) quasi-static space charge.

In addition to the higher irradiation of the room (as compared to bremsstrahlung-mode operation), the electron-mode presents another significant benefit. The rise-time appears to be faster. Evidence for this is shown in figure 11, where dose-rate measurements -- taken with a Cerenkov detector in electron mode, and with a plastic scintillator in photon mode -- are compared.

Conclusion

A good deal of thought and discussion is currently being generated on possible designs for new SREMP simulation techniques. While this is undoubtedly a healthy development, the authors would like to stress that the AURORA facility remains a significant and ever-improving source of data relevant to SREMP environments and coupling. Tactical work using auxiliary sources and strategic work using the electron mode continue to provide a steady stream of information and new techniques which bear directly on problems of current interest.

Other existing radiation sources -- such as HERMES II, which offers less energy, but which can be fired outdoors, eliminating the shorting effect of metal walls -- are, and should be, under consideration for use in SREMP testing. Also, development of new radiation-source concepts is taking place, at Harry Diamond Laboratories[31] and elsewhere. All these alternative sources can, and no doubt will, be used in conjunction with the techniques -- auxiliary sources and electron mode -- outlined in the above. However, for the time being, AURORA still dominates the SREMP scene.

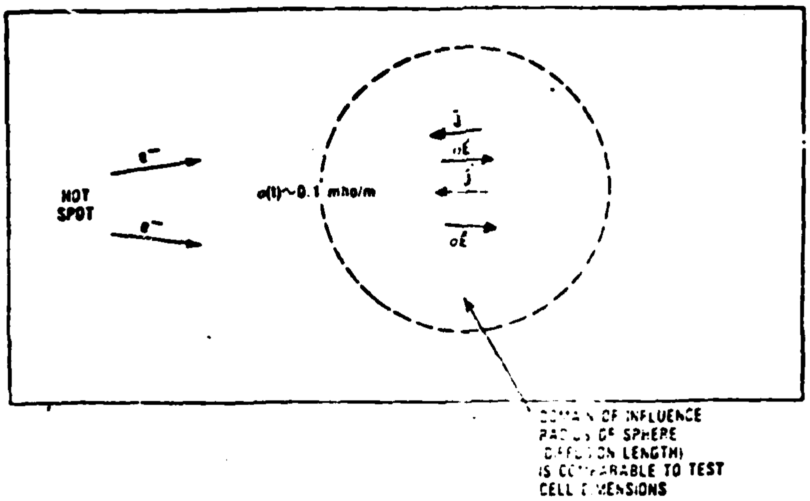

Figure 9. When electrons are injected into the AURORA test cell, the conductivity is so high that "local effects dominate".

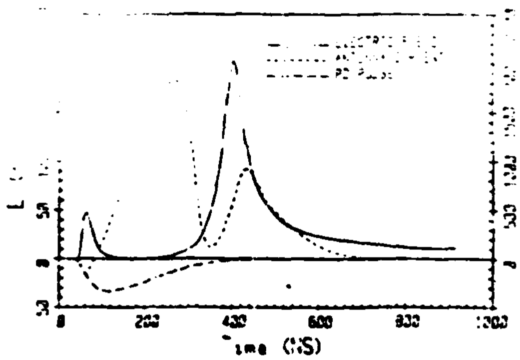

Figure 10. Cylindrical antenna current response, electric field measurement and photodiode measurement during direct electron injection AURORA shot.

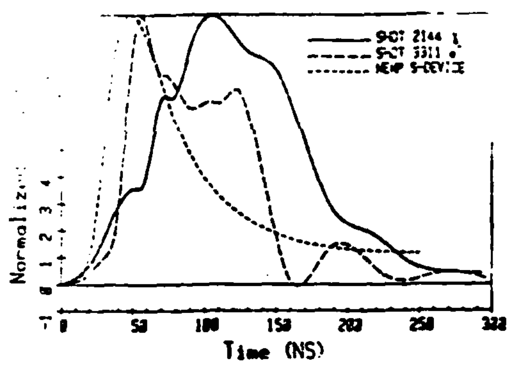

Figure 11. Rise time comparisons between various radiation sources. AURORA gamma mode pulse is from a single-source shot made during the July 1976 series. The electron mode pulse is from the March 1981 series.

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